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CFD ANALYSIS OF A DUCTED SPHERICAL HELICAL TURBINE FOR MICRO-HYDROPOWER

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ABSTRACT

Recently, a micro-hydropower generation system has been introduced for generating electricity by installing a spherical helical turbine in a water pipe line having a circular cross section. In this study, flow analyses through two ducted spherical helical turbines were reviewed to improve the performance of the turbine. The grid generation that determines the accuracy of the solution was performed using ANSYS ICEM-CFD and flow analysis was performed using ANSYS CFX V14.5. For CFD analysis, shear stress transport(SST) turbulence model was used. The performance of spherical helical turbine in water depends on the inlet water velocity of turbine. More fluid energy was concentrated in the turbine than with duct. In addition, flow analysis was performed by designing the same flow rate to compare the circular duct and the rectangular duct. As a result, using rectangular duct over circular duct improved performance by about 4.7%. It was also obtained that the use of the rectangular duct would increase the performance of spherical turbine by approximately 77.3%. Through the vortex structure analysis, it was confirmed that the vortex inside the turbine was reduced due to the use of the duct, thereby improving the performance of the turbine. In the future, it will be necessary to verify the performance of the spherical helical turbine by experiment, and it is expected that the spherical helical turbine with excellent performance will be developed by continuous research.

***KEYWORDS:** Micro-Hydropower, Spherical Helical Turbine, Duct, CFD, Transient Analysis & Power Coefficient*

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Original Article

INTRODUCTION

The turbines used in small hydroelectric power generation have horizontal-axis turbine and vertical-axis turbine based on the rotation axis direction. Vertical-axis turbines are Savonius turbines using drag, and Darrieus turbine and helical turbines using lift. Savonius turbine is structurally the simplest turbine and is generally driven by facing the blade of semi-cylindrical type. Savonius turbine has the advantage of low rotation speed and low noise because rotation speed cannot exceed flow rate. Darrieus turbine is a structure that drives by arranging blades with airfoil like wing shape of an airplane. It has a disadvantage of having difficulty in initial driving, it is used for power generation because the number of rotation is high after initial driving. The helical turbine is the advanced form of Darrieus turbine and the blade is made up of helical structure. Gorlov's study suggests that helical turbines increase energy efficiency by 20 to 35% over Darrieus turbines [1]. Figure 1 represents the shape of 3 typical types of vertical-axis turbines. The helical turbines have a cylindrical type that is widely used for tidal power generation and a spherical helical type that is widely used for micro-hydropower in circular pipeline [5].

Among the methods to increase the efficiency of turbine, there is a method to install ducts on turbine. This is a method of increasing the flow speed by reducing the diameter of the flow path using venturi effect. This allows

the higher efficiency to be obtained by concentrating the fluid energy of the large area on the small area, and it is economical because it can obtain the same efficiency with a turbine smaller in size than the turbine in the case of no duct. In addition, the torque fluctuation of the turbine is reduced, thereby enabling stable development and using ducts as a support without installing a separate support. Sounthisack Phommachanh et. al. was conducted through experiment and numerical analysis on the effect of using ducts in vertical-axis turbine [2]. The power coefficient before using the duct was 0.23 and the power coefficient was 0.45 when using the duct. It was confirmed that the performance of the turbine was improved by using the duct. Kirke compared the ducted Darrieus turbine and the helical turbine in the tidal power generation [3]. The micro-hydropower generation system using the flow pipeline is installed in the open waterway of the river, thereby having high energy density and securing stable water volume, so a rotating rotor with low flow loss is developed and installed in the flow pipeline. The energy is generated by the rotation force generated when the rotor rotates, and the rotation energy caused by the free flow rotates the rotor impeller. Figure 2 exhibits the outline of the floating pipe type micro-hydropower system installed at the open water channel like river [4]. In this study, the spatial helical turbine developed in the previous study was applied [5]. In order to maximize the output of the small hydropower generator, the power generation is proportional to the cubic power of the inlet flow rate of the turbine, so the flow rate into the turbine should be increased as much as possible [6]. For this purpose, the shape of ducts that can maximize the flow rate of turbines was optimized through numerical analysis [7].

(a) Savonius Type **(b) Darrieus Type** **(c) Helical Type**

Figure 1: Classification of Vertical-Axis Turbine for Micro-Hydropower.

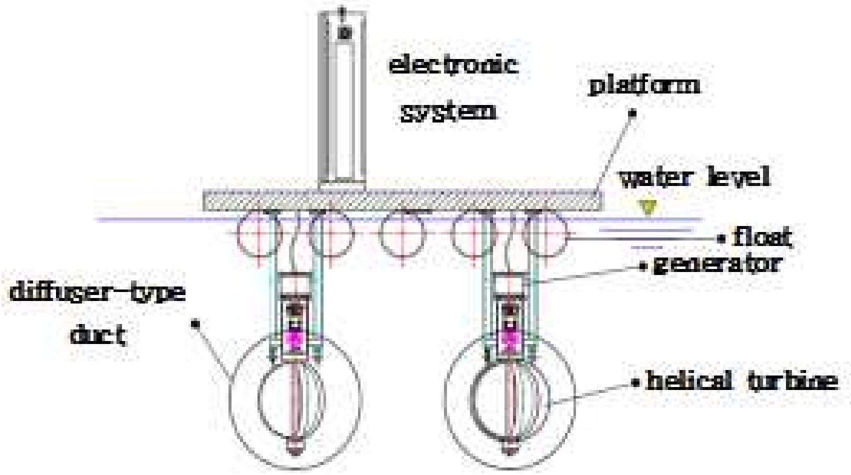


Figure 2: Conceptual Diagram of Micro-Hydropower System with Spherical Helical Turbine [4].

THEORY FOR CFD ANALYSIS

Governing Equations for CFD Analysis

The flow analysis was performed to optimize the shape of ducted spherical helical turbine and compare the performance, and the 3-dimensional flow analysis was performed to obtain more accurate analysis results [8]. The governing equations applied to grasp the flow characteristics of ducted spherical helical turbine are the continuity equation and the momentum equation and are expressed as follows [9].

Continuity Equation

$$\frac{\partial\rho}{\partial t} + \nabla \times (\rho u) = 0 \quad (1)$$

Momentum Equation

$$\frac{\partial}{\partial t}(\rho u) + \nabla \times (\rho u \times u) = -\nabla p + \nabla \times \tau + S_M \quad (2)$$

where S_M means momentum source port, and the τ is associated with the strain rate, as in the following formula:

$$\tau = \mu[\nabla u + (\nabla u)^\tau - \frac{2}{3}\delta\nabla \times u] \quad (3)$$

Analysis Technique

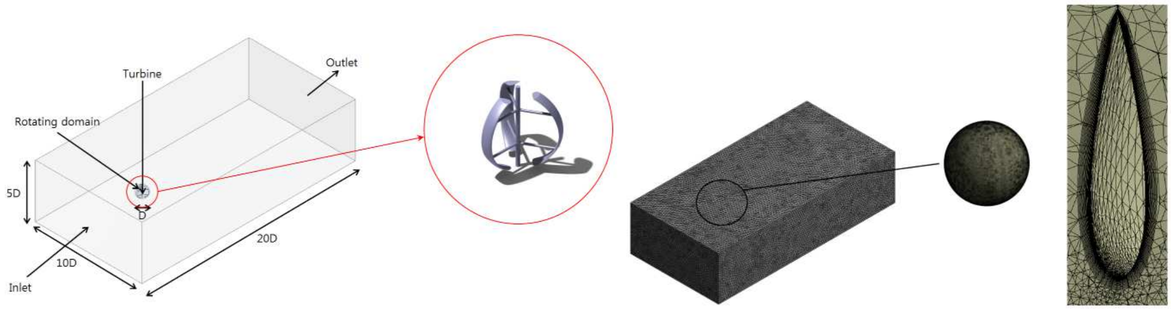
In the case of Turbulence model, the hybrid model combining the existing k-ε model and Wilcox model, the Shear Stress Transport(SST) model, was used to calculate the flow more accurately in the area near the turbine blade. The k-ε model is not suitable for the flow of separation and rotation in the boundary layer, and in the case of k-ω model, it is advantageous to predict the boundary layer flow better than the k-ε model. The SST model predicts the shear stress transport process of turbulence in a limited sense to prevent excessive prediction of eddy viscosity and simulates it relatively accurately [9,10].

$$-\overline{u_i{}'u_j{}'} = \nu_t\left|\frac{\partial\bar{u}}{\partial y}\right| \text{ and } \nu_t = \frac{a_1 k}{\max(SF_2,\ a_1\omega)} \quad (4)$$

The rotating spherical helical turbine region was used as a sliding mesh technique, and the GGI interface technique was applied to transfer flow data to the non-rotated region. In addition, transient analysis was performed to understand the performance of turbine according to time change. The time interval used in the transient analysis was the time for the turbine to rotate at 5°, and the total time was analyzed for the total time of the turbine to rotate at 6. It is known that convergence depends on tip speed ratio, but it usually converges when it is more than 5 rotations [11].

Analysis Model

The flow analysis of the spherical helical turbine in the duct was performed by 3D modeling. In the numerical analysis region, the rotating domain and the non-rotating domain are composed like Figure 3. In the case of non-rotating domain, the width was modeled as 10 times the diameter of turbine, the length of the inlet and discharge unit was 5 times and 15 times, respectively, and the upper and lower parts of turbine were 5 times the size of the width to remove the influence from the wall.



(a) Analysis Total Domain (b) Rotating and Non-Rotating Domain (c) Blade Region

Figure 3: Computational Domain and Mesh Generation of Spherical Helical Turbine.

SHAPE OPTIMIZATION OF CIRCULAR DUCT

In order to find the optimal shape of the circular duct to improve the performance of the spherical helical turbine, the flow analysis was carried out by installing the circular duct without the spherical helical turbine. As shown in Figure 4, the flow analysis was performed by setting the length of the duct(L1) and the inlet diameter(D1) of the circular duct as variables. The diameter of the turbine installation site was designed to be 1.4 m, taking into account the rotational size of the spherical helical turbine. The performance of the circular duct was determined by comparing the average flow rate at the turbine installation location. The mesh used in the flow analysis was composed of tetra grid in steady state. As analysis conditions, the inlet flow velocity was set at 2 m/s and the pressure at the outlet was set to atmospheric pressure. The flow analysis was performed by fixing the inlet diameter of the duct to 1.9 m and changing the length of the duct(L1). As shown in Figure 5, the average velocity at the turbine installation position was about 3.47 m/s and the average flow velocity improved by about 77% compared to the flow rate of 2 m/s. The longer the length of the duct, the faster the average flow rate, but the difference is not large. Considering the manufacturing cost of the duct, it was judged that the duct having a length of 2 m would be reasonable. After fixing the length of the duct to 2 m, the analysis was performed by changing the inlet diameter of the duct to 1.7 m, 1.9 m, 2.1 m. As a result, as shown in Figure 6, the average velocity was the fastest when the inlet diameter was 1.9 m. In this case, the angle of the circular duct is about 14°.

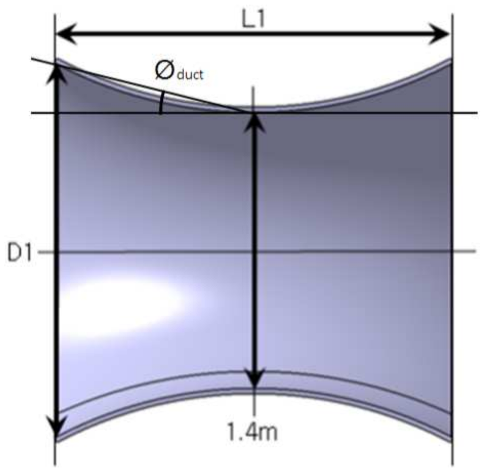


Figure 4: Design Parameters of Circular Duct.

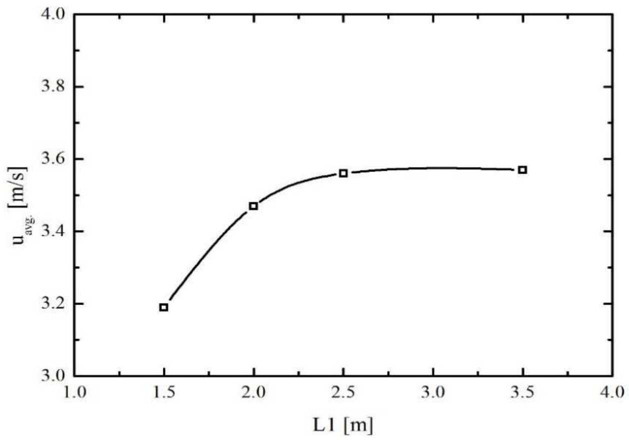


Figure 5: Distribution of Mean Velocity for Variation of Inlet Diameter in Circular Duct.

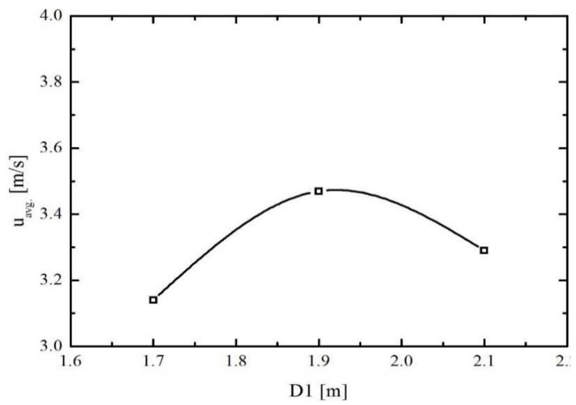


Figure 6: Distribution of Mean Velocity for Variation of Length in Circular Duct.

CFD ANALYSIS OF DUCTED SPHERICAL HELICAL TURBINE

Results of Circular Duct

The shape of the spherical helical turbine is shown in Figure 7 using an angle of attack 2°, helical angle 10°, and solidity 0.2, obtained through previous optimization study of spherical helical turbine [4]. The tetra grid was used for the flow analysis and transient analysis was performed. The grids used consisted of 4,912,614 nodes and 16,465,578 elements. As boundary conditions, the inlet velocity was 2 m/s and the outlet was set at atmospheric pressure. The rotation speed of the turbine was 48.72 rpm when the tip speed ratio was 1.25, which showed the highest power coefficient [4]. In the case of using the circular duct, the average power coefficient is 0.4630 as shown in Figure 8, and the performance was improved by about 69.3 % compared to 0.2734, the average power coefficient when the circular duct was not used. Figure 9 shows the velocity distribution at the azimuth angle showing the maximum power coefficient of the spherical helical turbine with the circular duct.

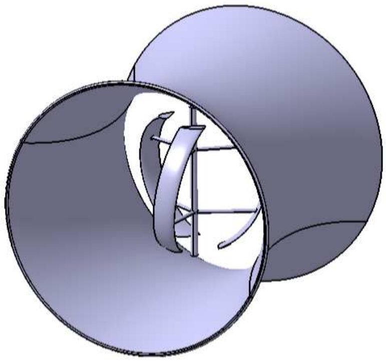
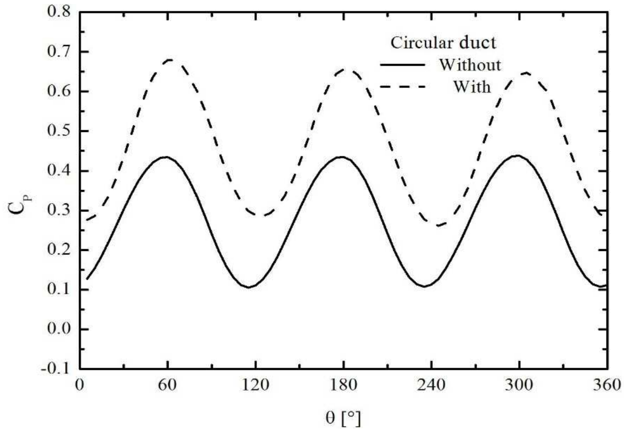
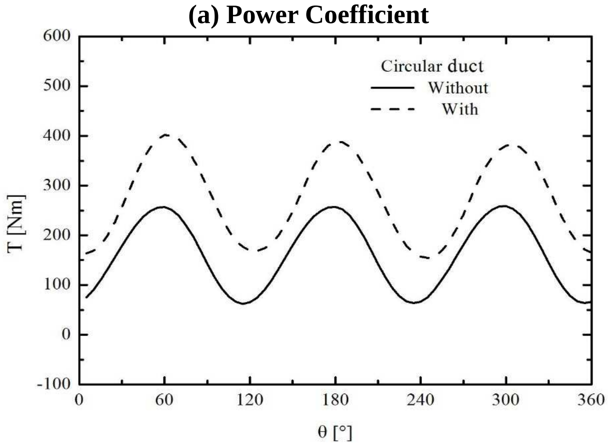


Figure 7: Geometry of Spherical Helical Turbine with Circular Duct.

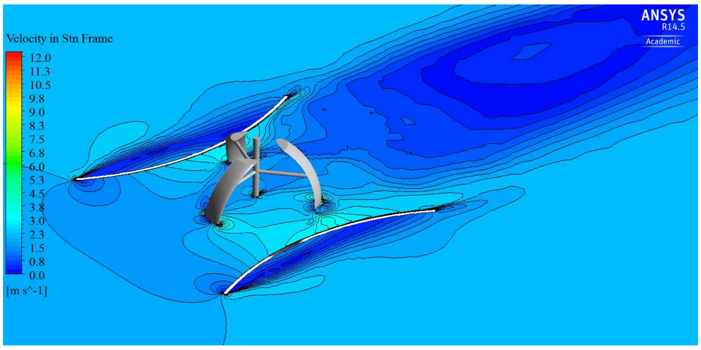


(a) Power Coefficient

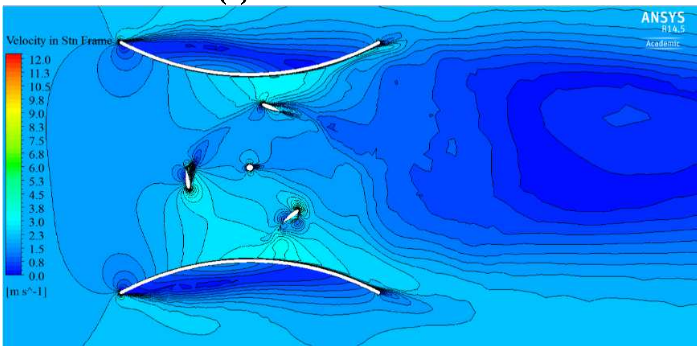


(b) Torque

Figure 8: Distributions of Performance for with and without Circular Duct in Spherical Helical Turbine



(a) 3 Dimensional View



(b) 2 Dimensional View

Figure 9: Contours of Velocity with Circular Duct in Spherical Helical Turbine.

Results of Rectangular Duct

In order to compare with the circular duct, the flow analysis of the rectangular duct was performed. In the case of the rectangular duct, the same cross sectional area as the circular duct was designed to allow the same flow to the turbine. The duct inlet is 1.68 m wide and 1.68m long, and the turbine installation site is 1.24 m wide and 1.24 m long. Like the circular duct, the length of the rectangular duct is 2 m and the angle of the duct is about 14°. The shape of the spherical helical turbine with the rectangular duct used is shown in Figure 10. The grid used for the flow analysis consisted of 4,169,998 nodes and 17,626,057 elements, and the boundary condition is the same as that of the circular duct. In the case of using the rectangular duct, as shown in Figure 11, the average power coefficient is 0.4847, which is 77.3 % better than the average power coefficient without the duct. Figure 12 shows the velocity distribution at the azimuth angle with the maximum power coefficient of the spherical helical turbine with the rectangular duct [12, 13].

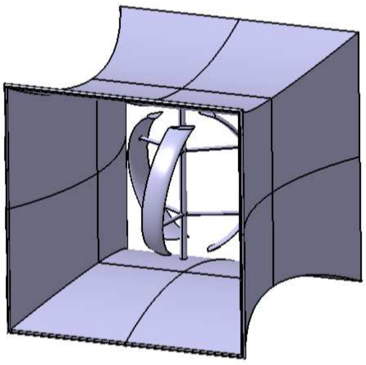
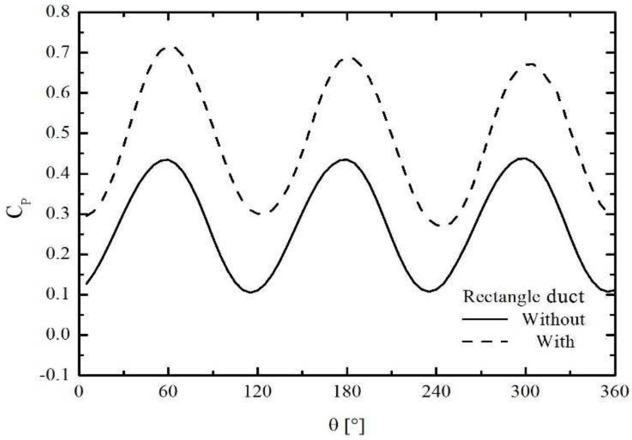
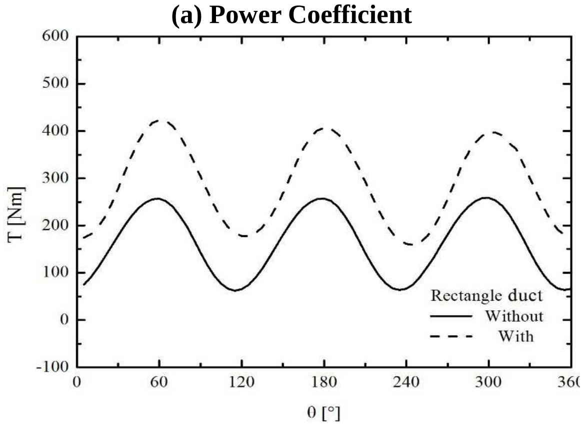


Figure 10: Geometry of Spherical Helical Turbine with Rectangle Duct.

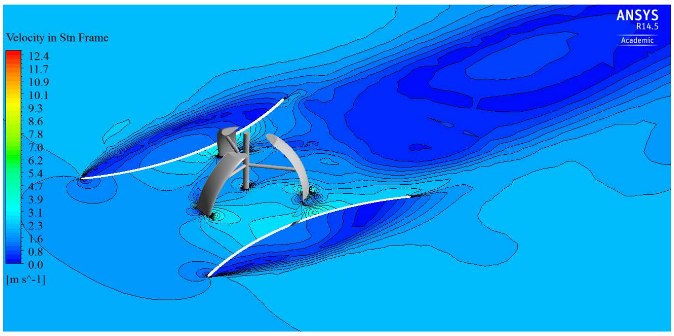


(a) Power Coefficient

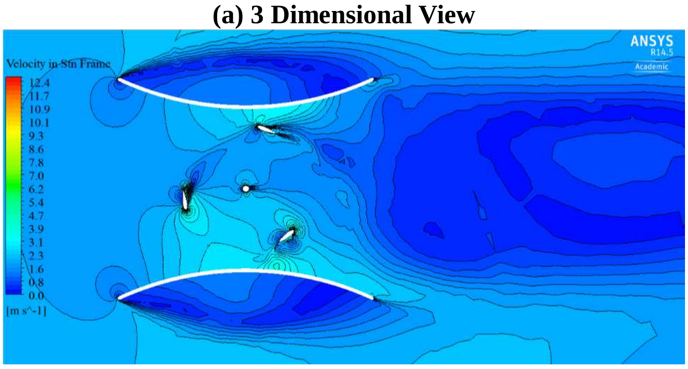


(b) Torque

Figure 11: Distributions of Performance for with and without Rectangle Duct in Spherical Helical Turbine.



(a) 3 Dimensional View



(b) 2 Dimensional View

Figure 12: Contours of Velocity with Rectangle Duct in Spherical Helical Turbine.

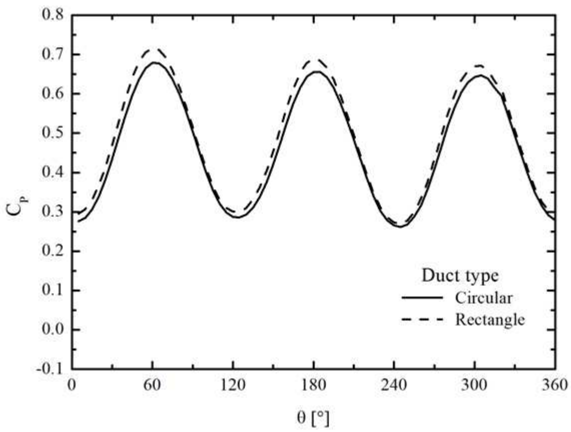
Comparison of Results of Two Ducts

Flow analysis of the spherical helical turbine using circular duct and rectangular duct showed that the turbine's performance improved due to the increased flow energy received by the ducts. Using the circular duct, the power coefficient improved by about 69.3 % and using the rectangular duct improved about 77.3 %. The average power coefficients of the circular duct and the rectangular duct were 0.4630 and 0.4847, respectively, and the performance of the rectangular duct was 4.7% higher. In the velocity distribution around the spherical helical turbine, the maximum velocities around the turbine blades of the circular and rectangular ducts were 12 m/s and 12.4 m/s, respectively. Although the same area was designed to equal the flow rate of the circular duct and the rectangular duct, the rectangular duct flow rate was faster than the circular duct due to the difference in the shape of the duct. Table 1 shows the power coefficient increase due to the use of the duct, and Figure 13 shows the results of the analysis of the performance variation according to the duct shape change in the spherical helical turbine.

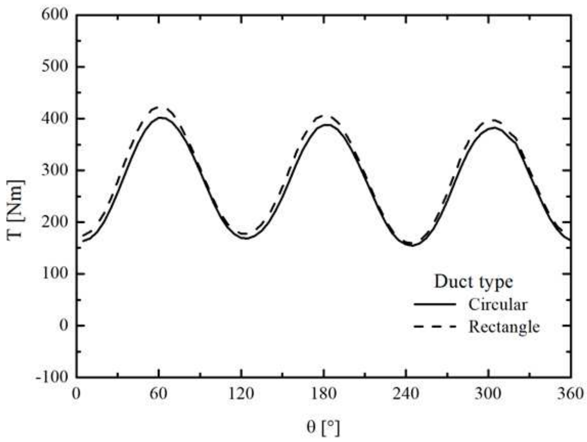
Vortices behind the spherical helical turbine create a flow resistance that results in energy loss, which degrades the turbine's performance. Therefore, the less vortex generation, the better. For this purpose, the vortex structure according to the presence or absence of the duct was applied by applying the vortex identification method called the swirling strength method [14]. Figure 14 shows that the vortex structure is small due to the use of the rectangular duct, and the performance of the spherical helical turbine is much improved when the rectangular duct is used.

Table 1: Results of Duct Effect on Spherical Helical Turbine

		Power Coefficient
Without Duct		0.2734
With Duct	Circular Duct	0.4630 (69.3%↑)
	Rectangular Duct	0.4847 (77.3%↑)

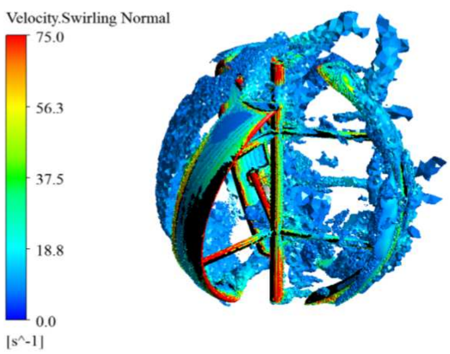


(a) Power Coefficient

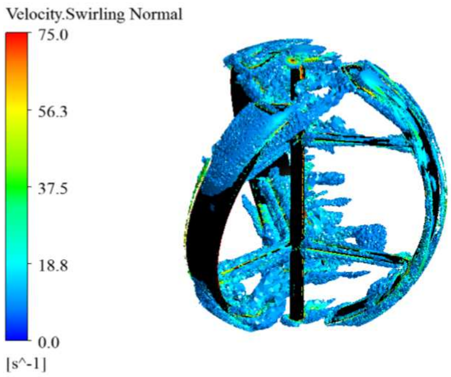


(b) Torque

Figure 13: Distributions of Performance for Circular and Rectangular Duct in Spherical Helical Turbine.



(a) Without Rectangle Duct



(b) With Rectangle Duct

Figure 14: Vortex Structure of Spherical Helical Turbine.

CONCLUSIONS

In this study, the performance variations of spherical helical turbine for the micro-hydro power were investigated. The use of two ducts with circular type and rectangular type improves turbine performance by concentrating more fluid energy on the turbine than without ducts. The performance of turbine was improved by about 4.7 % by using the rectangular duct rather than the circular duct. In addition, the average power coefficient of the spherical helical turbine was 0.4847 when the rectangular duct was used, and the performance was improved by about 77.3 % compared with the case without the duct.

The use of ducts has been shown to reduce vortex generation inside the turbine and improve performance of spherical helical turbine. In the future, it will be necessary to verify the performance of the spherical helical turbine by experiment, and it is expected that the spherical helical turbine with excellent performance will be developed by continuous research.

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